

Black Hole X-ray Transients

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The observations and theory of the exciting new class of galactic black hole X-ray transients is reviewed. Seven of these systems have measured mass functions or mass estimates in excess of stable neutron stars, making them excellent black hole candidates. Two of them have revealed “superluminal” radio jets. Study of the hard and soft radiation from these sources has given tight constraints on the physics of the viscosity of the accretion disk and promises firm proof that these systems contain black holes. This will allow us to search for black holes of more moderate mass and apply the knowledge of these systems to suspected supermassive black holes in AGN’s. The most plausible mechanism for triggering the outburst of black hole candidate X-ray transients is the ionization thermal instability. The disk instability models can give the deduced mass flow in quiescence, but not the X-ray spectrum. Advection models that can account for the quiescent X-ray spectrum are difficult to match with the non-steady state, quiescent Keplerian disks. Self-irradiation of the disk in outburst may not lead to X-ray reprocessing as the dominant source of optical light, but may play a role in the “reflare.” The hard power-law spectrum and radio bursts may be non-thermal processes driven by the flow of pair-rich plasma from the disk at early times and due to the formation of a pair-rich plasma corona at late times. The repeated outbursts in systems like GRO J0422+32 suggest some sort of clock, but it is unlikely that it has anything to do with a simple X-ray heating of the companion star. These systems typically have low mass secondaries and their evolutionary origin is still mysterious.

1. Introduction

In the past, Igor Novikov helped us to think about the inside of black holes and the methods to search for black holes. These subjects are today an active part of his legacy. In pursuing the astrophysics of black holes it is useful to remind ourselves about the subject of our quest lest we become too blasé or conclude the quest is finished.

Some black holes may arise from stars, but it is critical to remember that black holes are not ordinary stars, even exotic ones such as white dwarfs or neutron stars. They may come from matter, but they are not matter. Black holes represent the ultimate construct of strong gravity, of curved space time. Even though black holes harbor their secrets within the shroud of the event horizon, they are our conceptual link to the ultimate physics problem of singularities, fundamental notions of information as they evaporate, and to related concepts such as wormholes and closed time-like curves. It is thus of great importance to establish beyond any doubt that our Universe contains black holes and then proceed to study them, probe them, learn from them. Does our Universe contain black holes?

How does one go about the search for black holes? There are perhaps 10^{11} stars in the Galaxy, around 10^8 neutron stars, and maybe a million black holes left from the deaths of massive stars throughout the history of the Galaxy. The vast majority of these black holes will be isolated and thus hidden from any search. Logic suggests that because stars tend to congregate with like stars and black holes are thought to arise from massive stars that we should restrict our search to bright, hot, massive stars that might orbit a previously deceased companion, now a black hole. Massive stars are, however, rare. If the black hole is the product of a rare, massive star and it is in orbit around another intrinsically rare massive star while that star lives its relatively brief life then

the likelihood of the combination is low. The result is that there may be only one such system in our Galaxy and we have found it: the venerable Cygnus X-1.

It was with rather great surprise, then, that the last several years have taught us that the most common form of binary black holes candidates in the Galaxy, perhaps 100 to 1000 of them (Tanaka 1990), are black holes orbiting very small, but intrinsically common, half-solar mass K dwarfs. These systems are proving to be far more common than those like Cygnus X-1, but also to provide a fascinating laboratory to study the astrophysics of black holes.

We are one hundred percent sure we have discovered neutron stars. Have we discovered black holes? The probability is $P = 1 - \epsilon$. Many may think that $\epsilon = 0$ given the great work of HST (Ford *et al.* 1994) and the very clever result based on OH maser emission by Miyoshi *et al.* (1995) showing that active galaxies probably harbor massive black holes, as long suspected. In addition, at least six of the black hole transients to be discussed below have mass functions and hence minimum masses in excess of $3 M_{\odot}$, the neutron star limit. One might, however, argue that this evidence is still stubbornly circumstantial given that we simply know these objects have high gravity, large mass and no optical stellar counterpart. That might leave ϵ finite, perhaps a few percent. What do we need to provide incontrovertible *proof* that we have discovered black holes? The black hole X-ray transients may help to yield that proof.

Section 2 will give an overview of the observations. Some discussion of the relevant disk instability that probably triggers the outbursts and issues of self-irradiation of the disk and reprocessing is given in §§3 and 4. Section 5 describes the important lessons we have learned from the exponential decline about the physical nature of the disk viscosity. The curious “reflare” phenomenon is discussed in §6 and various aspects of the new advection solutions are given §7. The quasar-like hard power law is considered in §8. Section 9 describes some of the problems of progenitor evolution and related issues. A summary and outline of key issues is given in §10.

2. Observations

There are by now upward of 24 binary X-ray sources that have been suggested as black hole candidates (Tanaka & Lewin 1995; Chen *et al.* 1996). Six of these have measured mass functions that make them excellent candidates on that basis alone: AO 620-00 (Nova Mon 1975), $M_x > 3 M_{\odot}$ (McClintock & Remillard 1986); H 1705-250 (Nova Oph 1977), $M_x > 4 M_{\odot}$ (Remillard *et al.* 1996); GS 2000+25 (Nova Vul 1988), $M_x > 5 M_{\odot}$ (Filippenko, Matheson, and Ho 1995); GS 2023+338 (V404 Cyg), $M_x > 6 M_{\odot}$ (Casares & Charles 1994; Filippenko, Matheson, & Barth 1995); GS 1124-683 = GRS 1121-68 (Nova Muscae 1991), $M_x > 3 M_{\odot}$ (Remillard, McClintock, & Bailyn 1992); GRO J1655-40 (Nova Sco 1994), $M_x > 3 M_{\odot}$ (Bailyn *et al.* 1995). Other systems are placed in this category of black hole candidates because they share morphological similarities to these best candidates, for instance in terms of their light curves or spectra or have other confirming orbital data. Among the more prominent of these are LMC X-1, LMC X-3, GX 339-4, 1E1740.7, GRO J0422+32 (Nova Persei 1992), GRS 1716-249 (Nova Ophiuchi 1993), GRS 1009-45 (Nova Vel 1993) and GRS 1915+105. Note that after a hiatus between the discovery of the prototype A0620-00 and that of GS 2000+25 in 1988, candidate systems have been observed at the rate of about one per year. Since 1992 this has been in great part due to the effectiveness of the BATSE experiment on CGRO (Fishman *et al.* 1989; Harmon *et al.* 1994). This discovery distribution is a powerful argument for the maintenance of all-sky monitors in a variety of wavelengths.

Some of the black hole transients are known to have repeated, A0620-00 in 1916 and

1975, V404 Cyg in 1938, 1989, and perhaps in 1956, and all of them are suspected to have done so on time scales of one to a few decades. Some repeat in about a year, but with properties that may be different than the major outbursts. Nova Sco which was first discovered in 1994 is undergoing another outburst at this writing (May 1996).

Many of the outbursts are characteristically marked by a very rapid rise on the time scale of about a day and then a nearly exponential decline in soft X-rays with an e-folding time of 30–40 days. This behavior was clearly displayed by A0620-00, GS200+25 and Nova Muscae 1991. This form of the light curve is not universal, however. V404 Cyg had a very irregular light curve near maximum. Other potential candidates have shown other types of behavior, plateaus, triangles, etc (Chen *et al.* 1996). A caveat here is that the fast rise and 30–40 day decay is a signature of the soft X-rays. The hard X-rays, with a manifestly different physical origin, often display burst behavior, but with a rather different morphology than the soft X-rays. If one only monitored the hard X-rays, as is the recent circumstance with BATSE but without the regular coverage of Ginga, then the picture one gets is rather different. It is thus difficult to know whether or not the various light curve morphologies BATSE has observed belie a very different underlying structure of the object, accretion disk, outflows, coronae, etc. or whether or not one is seeing the tail, not the dog, because of energy response limited to $\gtrsim 20$ keV.

Another common feature of the light curves of the black hole candidates is a secondary brightening sometimes called a “reflare” at 60–80 days after maximum. This feature is not universal, but has been observed in all the sources with the canonical fast rise and exponential decay. Such a feature has never been observed in a neutron star soft X-ray transient with fast rise and exponential decline (Aql X-1 or Cen X-4), so there is some suspicion that it, too, is a signature of a black hole. V404 Cyg did not show this clear “reflare” and GRO 0422+32 showed only a bare flattening at ~ 50 days. On the other hand the “reflare” is a feature of the soft X-rays, presumably arising from the geometrically thin, optically thick inner accretion disk. Neither V404 Cyg nor GRO J0422+32 showed this soft X-ray component, but only the hard component which has some other physical origin. Some of the most interesting recent sources, the “super-luminal” sources GRS 1915+105 and GRO J1655-40 to be discussed below, showed irregular light curves in the BATSE band, with little correlating information.

Where observations have been sufficient, many systems have shown a “second maximum” in flux about 200 days after the primary outburst, among them A0620-00, Nova Muscae, and GRO J0422+32. This feature can be observed in both soft and hard X-rays, but the soft component is probably the low energy extension of the hard power law component and not at all from the accretion disk.

Two systems, GRO J0422+32 (Callanan *et al.* 1995) and Nova Vela 1993 (Bailyn & Orosz 1995; Della Valle, Benetti & Wheeler 1996), have shown yet more subsequent outbursts. These bursts have been detected primarily in the optical with very irregular coverage in other bands, soft and hard X-ray, radio. It is thus difficult to determine their true nature and the connection to previous flux peaks.

Many of the black hole candidates show a characteristic two-component spectral structure. One component is a power-law that extends to high energies >20 keV perhaps >400 keV. As mentioned above, this power-law presumably also extends to lower energies. Rising above this power law at low energies, a few keV, is an extra “ultra-soft” X-ray component that is thought to arise in the accretion disk. These two components do not vary in lock step. As the soft component declines more or less monotonically in the characteristic exponential decay, the hard component can vary non-monotonically. In some phases the behavior is complementary with the hard rising as the soft declines, reminiscent of the different “ γ -states” of Cyg X-1 (Ling *et al.*; Cray *et al.* 1996). In

particular it is important to note that while (one component of) the soft X-ray flux varies with the presumed mass flow rate in the inner disk, the power law component does not behave so simply. Its power may ultimately derive from the release of gravitational energy, but there remains at least some possibility that some of its energy derives from the black hole, perhaps in a Blandford-Znajek process (Blandford & Znajek 1977) .

As noted above there are exceptions to this characterization of the spectral behavior. The “ultra-soft” component was definitely absent in V404 Cyg and GRO J0422+32 and Nova Oph 1993. It is not clear whether this could be some geometrical effect obscuring emission from the disk or a true absence of the inner soft X-ray emitting accretion disk. Tanaka (1990) argues that the large amplitude noise of the emission from V404 Cyg near maximum, a characteristic of the power law that is suppressed when the soft X-rays dominate, is evidence that the inner disk component is absent. On the other hand GRO J0422+32 did not show the great variability of V404 Cyg. Nova Oph had a strange square light curve (Harmon *et al.* 1994), and it is not clear how it fits into the general scheme.

The short-term variability is also of great interest in these systems. Nova Muscae showed QPO’s at 3, 5, and 8 Hz (Miyamoto *et al.* 1993) and GRO J0422+32 at 0.04 and 0.1 Hz (Kouveliotou *et al.* 1993). The physics behind this variation is not yet understood, but it is clear that black hole sources and neutron star sources can have rather similar behavior and so the phenomena can not be restricted to any disk/magnetosphere interaction. There is some suggestion that this sort of time variability should be used to help classify the physical state of the system (van der Klis 1994, 1996).

Radio emission is also a ubiquitous feature of these systems where again no obvious parallel has been observed in the neutron star analog transient systems. The radio emission tends to follow the primary outburst, but most sources are not spatially resolved or well sampled temporally, so one does not know exactly where or when the radio was generated. This emission has been interpreted as an expanding synchrotron bubble (Han and Hjellming 1992), but it may all be better interpreted as a jet (Hjellming 1996). The relativistic particles might be created at some “working surface” that is somehow energized by power from the underlying system, but if jets are the rule then the fast particles almost certainly arise in the disk. The manner in which they are created is still not clear (§8).

More dramatically, two sources, GRS 1915+105 (Mirabel & Rodriguez 1995) and Nova Sco 1994 (Harmon *et al.* 1995; Hjellming & Rupen 1995; Tingay *et al.* 1995) have shown well-collimated “super-luminal” outflow. If the notion that we are dealing with black holes that emit power-law hard radiation and radio synchrotron radiation were not already sufficient, the discovery of these superluminal sources has completed the “mini-quasar” analogy. The X-ray light curves of both of these objects are somewhat unorthodox, but a well sampled soft X-ray light curve is lacking. GRS 1915+105 showed a long slow rise and then a outburst in the radio. It has a classic symmetric double-sided structure. Nova Sco had a rapid rise, but an irregular structure in which the radio bursts seems to correlate with a decline in the hard X-ray. It had an irregular hard X-ray light curve that bears no simple relation to the fast rise and exponential decline format. The radio structure is more irregular, with asymmetric blob structure.

Nova Muscae was well-sampled by Ginga and Sigma/GRANAT which detected both the ultra-soft flux and sufficiently high energy photons to sample the separate behavior of the power law tail. Miyamoto *et al.* (1993) have provided a decomposition of the light curve that is both rich in import for the physics of this and related systems, but also illustrative of the need for good sampling in both soft and hard X-rays as well as other bands, e.g. optical and radio.

The total power of Nova Muscae in all Ginga bands rose to a peak of 10^{38} erg s $^{-1}$ in about a day and then declined exponentially following the soft X-rays. The power went up at the “reflare” when the power law component was at a minimum, clearly establishing that the “reflare” is a phenomenon of the soft flux from the accretion disk. The “reflare” is also observed in optical and UV, so either the outer disk is involved or the mechanism of the inner disk can radiate in the optical. The total power went through a local minimum around day 170 and then another local maximum around day 200. This “second maximum” falls approximately on the extrapolation of the exponential. This may imply that the minimum is a decrease in flow rate or efficiency, rather than the 200 day maximum being an enhancement of either. On the other hand, in A0620-00 the “second maximum” at 200 days has an amplitude considerably in excess of an extrapolation of the exponential, so it may not be possible to draw general conclusions from this behavior.

Miyamoto *et al.* (1993) deconvolve the total power into the power law component, including an extrapolation to soft X-rays, and the component ascribed to the disk, the excess in soft X-rays above the power-law extrapolation. The soft X-ray flux ascribed to the accretion disk rose at the “reflare” as remarked above. In A0620-00 there is some suggestion that the soft X-ray flux declined with a steeper slope after the “reflare.” The data might also be compatible with an increase of the soft X-ray flux to a higher level at the time of the “reflare” with the same decline rate immediately after the “reflare” followed by a drop in flux to the original trend at about 100 days. For Nova Muscae the soft X-ray light curve shows a rise at the “reflare” followed by a decay with a somewhat shallower slope before the decline at about 140 days that precedes the “second maximum” at 200 days. GS2000+25 might show a similar behavior, but the sparse data is open to considerable interpretation. In the optical, A0620-00 showed a flatter slope throughout the exponential decline with an e-fold time of about 68 days, much shallower than the 30 days of the X-ray. The optical “reflare” was basically contemporaneous with the soft X-ray “reflare,” but the flux returned to the same trend as before the event within about 10 days. There was an unfortunate paucity of optical data on Nova Muscae. The origin of this “reflare” and the subsequent behavior of the light curve are not well understood, but may have something to do with the self-irradiation of the disk as will be discussed below (§4).

In Nova Muscae the disk flux began to plummet about 140 days after peak and faded to near the threshold of detectability by 170 days, corresponding to the minimum in the total power curve, a factor of over 100 in 30 days. There is no apparent contribution from the accretion disk to the “second maximum” at 200 days. This shows that this local maximum may be entirely ascribed to the power-law component and not to the disk, just the opposite of the “reflare.”

By deconvolving the spectrum into a disk and power law components the parameters that describe the disk model can be constrained. In particular the inner edge of the disk seems to be remarkably constant in a number of sources (GS2000+25; Nova Muscae; LMC X-3) when the soft X-ray luminosity and hence presumably the mass flow rate through the inner disk varies by factors of 10–100. There is only one obvious characteristic radius of the inner disk that should remain constant independent of \dot{M} and that is the last stable circular orbit that depends only on the mass of the black hole. Although somewhat uncertain, the absolute value of the derived inner radius is also consistent with the last stable orbit of a black hole of a few M_{\odot} (Miyamoto *et al.* 1993; Ebisawa *et al.* 1994). These observations are remarkably consistent with what one expects from a black hole and inconsistent with any kind of neutron star magnetosphere where the radius should adjust to the mass flow.

The hard component of the first outburst ascribed to the power-law source by Miyamoto *et al.* (1993) peaked before the soft flux in Nova Muscae and then declined rapidly, much faster than the disk flux. It went through a local minimum about five days after the power law peak, at about the time of the peak of the disk component as deconvolved by Miyamoto *et al.* and then rose again to begin a somewhat more slow decay. As the power law began this new trend the transient feature at 480 keV which has been ascribed to red-shifted annihilation radiation was detected (Sunyaev *et al.* 1992; Goldwurm *et al.* 1993). The power law flux began a more rapid decline again about 30 days after the peak and went through another sharp local minimum at about 40 days after peak. One wonders whether there was another annihilation event at that time, but there were no appropriate observations. The power law component went through a minimum from 70 to 100 days after peak and then began a rise to dominate the flux at the “second maximum” at 200 days.

Although the spectral index in the first peak and the “second maximum” were similar, it is possible that the physics of these two events were rather different. The first was associated with a radio burst and the apparent annihilation event. There are reasons to think that this event was associated with some form of strong dynamic outflow (Moscato & Wheeler 1994; §8). The “second maximum” may be more similar to the classic coronae discussed in the literature which are assumed to be in hydrostatic equilibrium (Liang 1990). Either of these configurations could interdict the inner portion of the disk, thereby preventing it from reaching to small radii where soft X-ray (\sim keV) can be radiated efficiently. This may be why the hard flux precedes the soft flux on the rise while the disk is “filling in” the inner region from which the outflow emerges and why the disk flux plummets before the “second maximum” as the “corona” swells to fill up the region previously occupied by the inner disk. Unfortunately, the observations of Nova Muscae were not sufficient to determine whether the radius of the inner edge of the disk increased as the “disk” component declined at 140 days (Ebisawa 1996).

3. Disk Instability

The most plausible origin of the outburst in these systems is thermal instability associated with the ionization of hydrogen and helium which is also thought to be the fundamental mechanism of dwarf novae where the central star is a white dwarf (Meyer & Meyer-Hofmeister 1981; Cannizzo, Ghosh, & Wheeler 1982; Smak 1982; Faulkner, Lin, & Papaliozou 1983; Mineshige & Osaki 1983; for a recent review see Cannizzo 1993a). This mechanism arises as matter accumulates in the disk and becomes denser and warmer. Hydrogen begins to ionize and this increases the opacity. In order to maintain thermal equilibrium between viscous heating and radiative losses the density must decrease to maintain the optical depth in the face of the rising opacity. This leads to the characteristic “S-shaped” curve in the plane of surface density and temperature. The surface density of the disk cannot decrease, however, since matter is accumulating. Instead the disk structure is driven out of thermal equilibrium. It heats until it attains a hot state where H is fully ionized and thermal equilibrium can be restored. The hot state has higher viscosity and this leads to a mass flow in excess of the transfer rate from the companion. The surface density and temperature decline until a critical density is reached where hydrogen begins to recombine. At this point a cooling instability ensues returning the disk to a cold state.

This cycle is imposed whenever the transfer rate from the companion would require a portion of the disk to be in the region of thermal instability. It depends quantitatively, but not qualitatively, on the nature of the viscosity. The instability in geometrically

thin Keplerian accretion disks generates heating waves that can propagate throughout the disk raising it to the bright, hot state that represents the outburst. This outburst can start in the outermost disk if the time scale for mass accumulation there is shorter than the viscous time scale. This depends on the mass transfer rate and the viscosity prescription in models. In other circumstances, the outburst can start in the middle or inner portions of the disk. After the outburst, the surface density profile becomes more concentrated at smaller radii. This leads to a decrease in the surface density at large radii and the subsequent cooling instability and cooling wave is automatically started near the outer edge of the disk. The subsequent cycles of heating and cooling to quiescence account for the basic observations of dwarf novae (Cannizzo 1993b) and candidate black hole transients (Mineshige and Wheeler 1989; Cannizzo 1993b, Cannizzo 1994, Cannizzo, Chen, & Livio 1995).

It is important to note that in the steady state the emission from the disk surface does not depend on the viscosity prescription (Shakura & Sunyaev 1973), but only on the local mass flow rate \dot{M} in the disk (aside from some boundary condition restrictions at the edges). In the time dependent case, the flux does depend on the viscosity prescription. This is a two-edged sword. It means the predictions of the models depend on the uncertain physics of the angular momentum transport, but it also means that observations coupled with models with particular viscosity prescriptions can constrain the physical nature of the viscosity. The success of this approach will be outlined below (§5). In general, the transfer rate into the disk will not be equal to the mass flow rate through any radius in the disk and in particular not to the mass flow rate through the inner disk that determines the X-ray luminosity in the black hole models. One must avoid analyzing time-dependent situations with convenient, but erroneous, steady-state assumptions.

There are various tests of the disk instability in the context of the black hole transients. The models naturally gives a rapid rise and slower decline in the soft X-ray and optical. They can give an exponential decay as observed in some sources (Cannizzo, Chen, and Livio 1995; §5). The mass transfer from the companion in A0620-00 greatly exceeds that attributed to the soft X-rays from the inner disk (Marsh, Robinson & Wood 1994; McClintock, Horne, & Remillard 1995). This shows that the disks are not in steady state in quiescence, a principle prediction of the disk instability models. There has been difficulty in detecting the cooling wave that should attend the decline (Cheng *et al.* 1992), but this may be because coronal heating yields a different color temperature than the effective temperature predicted by basic models.

4. Disk Irradiation

The question of the effect of disk self-irradiation is an important one for any source that emits intense X-rays, that is any neutron star or black hole system. In cases like Cygnus X-1 irradiation from the companion may also play a role, but this has not yet been quantitatively investigated. Irradiation from the companion to the disk is not important in the systems with small mass companions, but irradiation of the companion stars by the disk may be.

Van Paradijs and McClintock (1994, 1995) argue that the optical luminosity in black hole transients may be, in analogy to low mass X-ray binaries, dominated by X-ray reprocessing in the disk. Van Paradijs (1996) has extended this argument to investigate whether the disk irradiation can alter the critical transfer rate below which the disk instability sets in. If the disk is heated by irradiation it can be maintained in a stable, ionized state even if the mass transfer rate alone is insufficient to keep the disk ionized. On

the other hand, Cannizzo (1994) has argued that the irradiation in the disk is negligible based on his study of the viscosity parameter α and its relation to the decay time scales in dwarf novae and X-ray novae. Huang and Wheeler (1989) and Mineshige and Wheeler (1989) noted that disk instability models of black hole sources with no irradiation give ample optical luminosity.

A first step toward the understanding of irradiation in the context of time-dependent, irradiated disk models has been taken by Kim, Wheeler, and Mineshige (1996a,b). They adopt two simple models of the irradiation: direct irradiation from the innermost hot disk and irradiation as might be reflected by a corona or disk atmosphere or chromosphere above the disk. The X-ray luminosity of the irradiation is given by

$$L_X(t) = \epsilon \dot{M}_{in} c^2, \quad (1)$$

where the efficiency $\epsilon = 0.057$, and \dot{M}_{in} is the mass accretion rate at the inner edge of the disk R_{in} , taken to be $3r_g$ for a Schwarzschild black hole. For the indirect irradiation the assumption is made that the luminosity of Eq. 1 effectively arises from a point at the center of the disk ($R = 0$). The indirect irradiation flux is then given by

$$F_i(t) = C_X \left(\frac{L_X(t)}{4\pi R^2} \right), \quad (2)$$

where C_X is a constant. More sophisticated models incorporating radiative transfer would give $C_X = C_X(R, t)$ (see discussion in Tuchman, Mineshige & Wheeler 1990), but such time-dependent radiative transfer is too difficult at this time. For the indirect irradiation, the prescription of Fukue (1992) is followed. This model assumes that the irradiation from a hot, geometrically thin annulus near the inside of the disk can be approximated by that from an infinitesimally thin, filled, uniformly radiating surface centered on the black hole. For regions in the disk at distances much larger than the radius of the annulus, this leads to the following expression:

$$F_d(t) = (1 - A) \left(\frac{L_X(t)}{2\pi R} \right) \frac{d}{dR} \left(\frac{H(t)}{R} \right)^2. \quad (3)$$

For simplicity, we take the X-ray albedo, $A = 0.5$. The specific choice of albedo does not appreciably affect the disk structure since shadowing suppresses the direct irradiation (see below). Eq. (3) shows that the direct irradiation is a function of the gradient of the disk height and hence very sensitive to small variation in the disk profile. Once \dot{M}_{in} and hence $F_i(t)$ and $F_d(t)$ are determined, the irradiated flux is added to the flux generated internally in the disk by viscous heating through an implicit numerical method, and hence other disk physical variables are corrected in each time step (see Tuchman *et al.* 1990 and Mineshige, Tuchman & Wheeler 1990 for details). In this formulation, the irradiation fluxes are parametrized by two constants, C_X and A , which are, by assumption, independent of radius and time.

Kim *et al.* (1996a,b) show that even relatively mild irradiation from the inner disk can affect the overall disk evolution. Irradiation enhances depletion of mass from the disk during outburst, which results in a longer quiescent interval. It can also affect the slope of the declining light curve. More specifically, irradiation can affect the limit cycle by causing portions of the disk to linger in the intermediate temperature metastable “stagnation state.” Although the disks are in nearly steady state near maximum, the time dependent models show that this is not strictly so and this has important implications for the irradiation. There tends to be a local maximum in H/R at intermediate radii ($\sim 10^8$ cm) that causes the outer disk to fall in the shadow of the inner disk, even at the time of maximum X-ray flux. This strongly limits the effect of the direct irradiation. Direct irradiation does not play an important role in the outer disk during and after

the maximum of the outburst, but can affect the middle of the disk during the outburst. Since it is by assumption not influenced by shadowing, the indirect irradiation affects the overall disk evolution, including the outer disk, throughout its evolution. The indirect irradiation is, unfortunately, very uncertain because it depends on the X-ray scattering in coronae of unknown physical nature which Kim *et al.* have not considered.

Kim *et al.* have not explored the regime of strong indirect irradiation (large C_X) in any detail on the grounds that the light curve of the non-irradiated or only mildly irradiated models match the observations reasonably well. Such strong irradiation is likely to destroy this agreement, although this is a regime that should be explored more thoroughly. It is true that strong irradiation can heat the outer disk and stabilize disks that would otherwise be unstable to the disk instability for a given disk size and mass transfer rate as argued by van Paradijs (1966). Van Paradijs adopts a steady-state model for direct irradiation and hence his criterion for stabilizing the disks by irradiation may not apply to the transient sources. The time-dependence tends to yield disks with non-monotonic height profiles and hence shadowing of the outer disk by the inner and middle disk even in outburst when the disk is approximately in steady state. This suggests that transient sources should still follow the criterion given by, e.g., Smak (1983) neglecting irradiation. Aql X-1 represents an interesting case in point since it lies very close to the irradiated instability line determined by van Paradijs. One might argue that as a transient it should be governed by Smak's criterion and be well below the minimum transfer rate for stability. Aql X-1 has a variety of interesting properties that make it difficult to straightforwardly interpret it in terms of a disk instability (Tanaka and Lewin 1995), but it is worthy of closer examination in this respect.

Further study is necessary to understand the correlation of the optical activity to X-ray and radio observations. The irradiated models presented by Kim *et al.* are based on parameters chosen to reproduce the basic behavior of the optical light curve of A0620-00. They show that the disk instability is initiated in the outer portions of the disk. This means that the optical should begin to rise before any activity in harder bands. Mass flow is, however, enhanced in the inner disk before optical maximum, so soft and hard X-rays might well precede optical maximum. These models give inner disk temperatures of several million degrees near maximum, but this is not hot enough to provide sufficient soft X-rays. Other choices of disk parameters might give larger maximum flow rates and hence higher disk temperatures.

5. The Significance of the Exponential Decay

One of the interesting features of the black hole X-ray novae is the tendency to show an exponential decline. Simple models in which one quickly reduces the transfer rate to a hot disk with constant viscosity parameter α generate geometrically declining, not exponential, light curves. Even models in which the decline is driven by the cooling wave of the disk instability tend to have geometrically declining light curves with constant α . Mineshige, Yamasaki, & Ishizaka (1993) have argued that to produce an exponential decline, the angular momentum of the inner disk must be removed at a rate proportional to the angular momentum. They note that this tends to be the behavior of disk instability models with $\alpha = \alpha_0(H/R)^n$ with $n \sim 1 - 2$. Cannizzo (1994) has also addressed this argument by noting that both dwarf novae and the black hole transients have exponential declines. Cannizzo concluded that to reproduce the exponential one needs $\alpha \propto R^\epsilon$, with $\epsilon \sim 0.3 - 0.4$, which is consistent with Mineshige *et al.* Cannizzo carried the argument one step further, however, by making the case that the precise value of ϵ that leads to exponential decline is itself a function of other parameters of the problem such as the

transfer rate and inner disk radius. From this he concluded that exponential decline requires some form of feedback to operate in the disk to give just this behavior. This may hint that the angular momentum transport process is non-local, as the theories where internal waves play a critical role imply (Vishniac & Diamond 1993).

These arguments have been extended significantly by Cannizzo, Chen, and Livio (1995). Cannizzo *et al.* have shown that finely zoned (non-irradiated) models give a cooling front width $w \propto \sqrt{HR}$ and that the light curve in decline can be exponential only if there are certain conditions on α . Cannizzo *et al.* express the speed of the cooling front as,

$$V_f = \frac{2}{3}\alpha_0 \left(\frac{H}{R}\right)^{n+1} \frac{c_s}{w} R, \quad (4)$$

where $H = c_s \Omega$ is the vertical scale height at radius R , c_s is the sound speed, Ω the Keplerian angular velocity, w is the width of the cooling front and the viscosity parameter is given by $\alpha = \alpha_0 (H/R)^n$. They argue that the relevant sound speed is that dictated by the temperature of recombination in the matter just preceding the cooling front which is essentially constant, giving $(H/R) \propto R^{1/2}$. Assuming the criterion for exponential decay to be $V_f \propto R$ the relation $w \propto \sqrt{HR}$ then yields the observed exponential decay only when $n = 3/2$.

Vishniac and Wheeler (1996) have amplified this issue by showing that the cooling front speed is set by the rarefaction wave (in surface density Σ) that precedes the cooling front and that, in turn, determines the cooling front width, rather than the other way around. They show that the condition $V_f \propto R$ does lead to an exponential decline in the mass in the inner hot region and an exponential decline in \dot{M} , but that the speed of the front depends on opacities. For Kramer's opacity, the value of n that leads to an exponential decline is closer to $n = 1.65$ rather than 1.5. This preferred value of n is consistent with the theory of angular momentum transport by an internal wave-generated dynamo driven by tidal instabilities at the outer edge of the disk (Vishniac, Jin, & Diamond 1990, Vishniac & Diamond 1992). Vishniac and Wheeler argue that the cooling wave propagation depends on the viscous flow in the hot state and is nearly independent of the actual cooling process and of the state of the disk in the cool, quiescent material that accumulates in the wake of the inward-propagating cooling wave. The speed of the cooling waves is determined by the rarefaction wave that precedes them and is approximately $\alpha_F c_F (H/R)^q$, where α_F is the dimensionless viscosity, c_F is the sound speed, and all quantities are evaluated at the cooling front. The scaling exponent q lies in the interval $[0, 1]$, depending on the slope of the (T, Σ) relation in the hot state; however, q will be close to $1/2$ for most models of the disk hot state. These results are insensitive to the structure of the disk outside of the radius where rapid cooling sets in. Vishniac and Wheeler conclude that the exponential luminosity decay of cooling disks is probably compatible with the wave-driven dynamo model. It is not compatible with models with separate, constant values of α for the hot and cold states.

There are several conclusions to be drawn from this work of Cannizzo *et al.* and Vishniac and Wheeler. First, the whole analysis is predicated on the assumption that a cooling wave exists in the decline of the light curve of transient black hole candidates and related systems. While the evidence is indirect, one can thus regard the exponential decline as a strong argument that a cooling wave is the fundamental mechanism of the decline of these transients. Since the cooling wave is one of the principal aspects of the disk instability, the exponential decay adds to the evidence that the accretion disk ionization instability is the underlying physical cause of the transient outburst phenomenon.

Another important general conclusion is that the study of accretion disks with phe-

nomenological models for the angular momentum transport have provided crucial constraints on the nature of the viscosity. The quantitative and even qualitative behavior of the black hole models depends on the prescription for α . In the case of a double valued, but radially constant prescription, the outburst will tend to occur in the inner disk, yielding a somewhat slower rise phase and more symmetric outbursts. A prescription in which $\alpha = \alpha_0(H/R)^n$ will give very small values of α in quiescence where H/R is found to decrease inward. This will yield a very long viscous time in the inner disk and promote outbursts that begin in the outer disk and propagate inward. This yields model outbursts with rapid rise and slower decline, in accord with the observations for the optical and soft X-ray light curves of the many of the X-ray novae. The conclusion of Vishniac and Wheeler that the exponential luminosity decay of cooling disks is not compatible with models with separate, constant values of α for the hot and cold states thus constrains the nature of the outburst and suggests that for the black hole cases, in particular, ignition of the heating on the outside (logarithmically) is to be expected.

More specifically, these analyses support the conclusion that the exponential decay of the luminosity of black hole disk systems following outbursts is consistent with a local law for the dimensionless disk viscosity $\alpha \propto (H/R)^n$ if, and only if, n is approximately $3/2$. This scaling for α implies that disk systems in general should exhibit approximately exponential luminosity decay from peak luminosity whenever the hot state opacity follows a simple power law. This result is apparently compatible with the internal wave driven dynamo model for disk viscosity.

Cannizzo *et al.* (1995) have shown that the slope of the exponential is a function of M/α_0 , where M is the mass of the central object and α_0 is the coefficient in the local viscosity law. Cannizzo *et al.* argue that $\alpha_0 \sim 50$ is a universal constant. Understanding why this coefficient differs so significantly from unity will be a challenge for the dynamo models. If Cannizzo *et al.* are correct, then the slope of the exponential gives a measure of the mass of the central objects. For the black hole sources, the result is compatible with $M \sim 5M_\odot$ and the conclusion that A0620-00, GS2000+25, and Nova Muscae all have very similar black hole masses (§9).

These new insights into the nature of the viscosity of the black hole sources also give a new perspective in which to ask questions of other astrophysical sources. The so-called “TOADS,” tremendous outburst amplitude dwarf novae (Howell, Szkody & Cannizzo 1995) give evidence for especially low viscosity. Another internal wave-driven mechanism, the incoherent dynamo, (Vishniac & Brandenburg 1995) gives a minimum value for α_F . This may provide a floor opacity to the TOADS and they in turn may provide some direct constraints on the non-local nature of the wave-driven mechanisms.

Another problem of interest is that of disks in QSO’s or AGN’s. In that context there is no obvious companion to generate internal waves by tidal instability. Some other mechanism to generate internal waves, perhaps stellar collisions with the disk, must be sought.

In any case, the understanding of the import of the exponential decline of the black hole sources marks the end of a chapter in the study of accretion disks and opens up a new range of topics to be explored with some confidence that we do have the first rudiments of understanding of the viscosity of accretion disks.

6. The Reflare

The “reflare” phenomenon seems to be a common feature of the black hole transients that show the classic fast rise and exponential decline. This feature calls for a physical explanation in general and raises the expectation that it might prove to be an interest-

ing physical diagnostic. There have been four studies of the phenomenon of the “reflare” observed in the decay of many black hole X-ray novae: Chen, Livio & Gehrels (1993), Augusteijn, Kuulkers & Shaham (1993), Mineshige (1994) and Kim, Wheeler & Mineshige (1996b).

The first two studies assume that X-ray irradiation can modulate the mass transfer rate from the companion by irradiating the companion during the rise, maximum and the early stage of the outburst decay to produce the “reflare” (mass transfer burst model). Chen *et al.* (1993) do not discuss in any detail the observable implications of their model such as optical or X-ray light curves. It is not clear, for instance, what the optical response of the disk would be, nor the degree to which even a sharp burst of added mass will be spread by the finite viscous response of the disk (especially when the outer parts of the disk are in the cold state) so that any later effect in the X-rays will be delayed with respect to the optical and very spread out in time. There are also questions of whether the disk blocking they invoke to account for the delay of the “reflare” is consistent with their estimates of mass transfer and energetics that depend on irradiating the companion. Similar issues arise in their model for the “second maximum.”

Augusteijn *et al.* (1993) suggest an oscillation of the light curve in the decay in which each successive burst is a “reflection” of the previous burst that heats the companion and drives more mass transfer after some time delay. This model seems to be remarkably reminiscent of the recently discovered “mini-outbursts” in GRO J0422+32 (Callanan *et al.* 1995) and Nova Vela 1993 (Bailyn & Orosz 1995; Della Valle, Benetti, and Wheeler 1996). Augusteijn *et al.* (1993) even predicted bursts in Nova Per in August 1993 and December 1993, as observed. Augusteijn *et al.* (1993) deserve credit for drawing attention to the fact that there may be some “clock” underlying the bursts in Nova Per and perhaps other objects, but there are still open questions concerning their particular model. One point that requires clarification is that Augusteijn *et al.* (1993) did not clearly differentiate the “reflare” from the “second maximum” as we are defining them here. They first adjust parameters of their model to fit the “reflare” of GS 2000+25, but then calibrate the model on the “second maximum” of GRO J0422+32 in order to “predict” the later outbursts. It is not at all clear that the “reflare” and the “second maximum” involve similar physics since the “reflare” is a feature only of the soft X-rays and optical/UV and the “second maximum” is dominated by the power law hard X-rays, although it also has an optical component (§2). The later mini-outbursts may be related to the “second maximum,” as Augusteijn *et al.* (1993) argued, but their spectral response is not yet well established. They may be purely optical phenomena. In addition, Augusteijn *et al.* (1993) predict bursts of decreasing amplitude whereas, as Bailyn & Orosz (1995) point out, the observed optical bursts have nearly constant amplitude. Augusteijn *et al.* (1993) also predict a burst on 21 April, 1993 for GRO J0422+32, and no such burst was observed. The models of Augusteijn *et al.* (1993) also do not consider the state of the disk, especially in its cool, quiescent, low-viscosity state, in a self-consistent way.

Unlike the pictures proposed by Chen *et al.* (1993) and Augusteijn *et al.* (1993), the models of Kim *et al.* (1996b) for the optical “reflare” require that the outer disk and the L_1 point are blocked by the inner disk from receiving any direct irradiation throughout the decay phase prior to the “reflare.” This contradicts the hypothesis of the X-ray-irradiated mass transfer burst models, that the L_1 point be irradiated. Kim *et al.* (1996b) find the companion to intercept an angle of about 10° from the center of the disk. Near maximum light, the disk blocks all angles less than about 5° . Kim *et al.* estimate that the companion receives $\lesssim 10^9$ erg cm $^{-2}$ s $^{-1}$ of intercepted irradiation at maximum. Recent studies of the evolution of irradiated low mass companions show that the mass

transfer rate will increase as the companion's atmosphere expands upon heating if the irradiation fluxes are $\gtrsim 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Podsiadlowski 1991) or $\gtrsim 10^9 \text{ erg cm}^{-2} \text{ s}^{-1}$ (Hameury *et al.* 1993). Thus the disks always shadow the L1 point and the intercepted flux may be so low as to be unable to engender any appreciable structural changes in any case.

Mineshige (1994) suggests that the “reflare” is caused by a sudden increase of viscosity as the disk is irradiated and by a concurrent mass transfer burst instability. The origin of this sudden increase in viscosity by a factor of 2 to 4 in extended portions of the disk, is, however, not clear. In the irradiated models presented of Kim *et al.* (1996b), there is a sudden increase of the viscosity, but it is confined to the zone that undergoes the “reflare.” The viscosity parameter α changes by a factor ~ 4.8 from ~ 10 days prior to the “reflare” to the maximum of the “reflare.”

The irradiated disk instability models of Kim *et al.* can reproduce the optical “reflare” observed in A0620-00. In these models the optical “reflare” results from an intrinsic property of the disk instability, the “stagnation” phenomenon whereby the disk does not directly jump from the hot down to the cool state, but stays at an intermediate temperature due to an increase in the specific heat in the partially ionized matter. Portions of the disk can then jump from this “stagnation” state back to the hot state giving the optical reflare. In the irradiated accretion disk models, the stagnation is reinforced by the continuous heating from the irradiation reflected by the disk corona or chromosphere. This modulation of the outer disk gives no direct way to modulate the mass flow rate in the inner disk in order to produce a correlated soft X-ray “reflare” as commonly observed in these black hole candidates, a problem that plagues other models of the “reflare.” Kim *et al.* have shown, at least, that the possibility of optical flaring in the outer disk should be considered as part of the relevant physical processes.

We do not yet have a complete understanding of the physical mechanism of the “reflare” (or subsequent flares). No model yet proposed can naturally account for why the “reflare” seems to coincide with the sudden drop in the hard X-ray flux in Nova Muscae (Miyamoto *et al.* 1993). Nevertheless, these irradiated models show that effects in the disk alone can give optical outbursts that may be related to the optical flares seen. They also give us a new perspective from which to consider questions of the irradiation of the companion.

A critical question remains as to the frequency of occurrence and the physical nature of the repeated flares of systems like GRO J0422+32 and Nova Vela. Since coverage of these systems at late times is spotty, these sorts of subsequent outbursts could be common. The spectral coverage is even more dismal. We have very little idea whether these bursts are primarily an optical phenomenon, or whether they have an associated soft or hard X-ray component as well. Such observational data is critical if we are to understand whether these repeated bursts are a product of the outer disk, the inner disk, and related to the disk instability, to a tidal instability, to a mass transfer instability, to a combination of these processes, or to some other process entirely.

7. Matching with Advective Solutions

The models of Kim *et al.* (1996a,b) give an inner region that remains in the hot ionized state even though the bulk of the disk drops into a cold, low-viscosity, quiescence. The cooling wave slows as the density is depleted in the inner disk and it does not reach the inner edge before the next eruption occurs. The mass accretion rates given by these models, $\sim 10^{11} \text{ g s}^{-1}$ for non-irradiated models and $\sim 10^9 \text{ g s}^{-1}$ for irradiated models, agrees rather well with that deduced for A0620-00 in quiescence by McClintock *et al.* (1995), but the models give too low a temperature which McClintock *et al.* (1995)

estimate to be $\sim 2 \times 10^6$ K. This problem has been discussed by Lasota (1995). The behavior of this slow inner cooling wave may be sensitive to the viscosity parameter and other model parameters in a manner that needs to be explored.

A possible solution to the problem of the X-ray emission is provided by hot flows in which quasi-radial advection of thermal energy is a key component as reviewed by Abramovicz in these proceedings (Narayan and Yi 1994; Abramovicz *et al.* 1995; Artemova *et al.* 1996). Narayan, McClintock, and Yi (1996) obtain a fit to both the optical and X-ray spectra of A0620-00 in quiescence by invoking a hot two-temperature advective disk solution in the inner disk matched to a steady state Keplerian disk in the outer portions that provides the optical luminosity. The advective solution, however, is of low efficiency and requires a mass flow rate of $4 \times 10^{14} \text{ g s}^{-1}$, much higher than the estimates based on steady state, geometrically thin, optically thick disks by Marsh *et al.* (1994) and McClintock *et al.* (1995) and much higher than the quiescent flow rates obtained by Kim *et al.* (1996a,b). The steady-state disks appended to the advection solutions by Narayan, McClintock & Yi are not consistent with the quiescent state of the disk being modeled. The disk is almost surely not in steady state in quiescence. Note that, even if advection is a factor at some phases of quiescence, the disk instability associated with ionization of hydrogen and helium and its role during outburst evolution can not be avoided for the conditions that are thought to exist in quiescence.

Lasota, Narayan, and Yi (1996) address these issues by presenting models with a radially constant mass flow rate specified as a parameter. They explore conditions in which the outer cool disk can be in a globally stable steady state at low viscosity. They point out that such configurations can be thermally unstable depending on the inner boundary where the advection solution takes over. Alternatively, they might be triggered into disk instability by some enhancement of mass transfer from the companion star. They note that the disk is too cool, ~ 2000 K, to provide the the observed quiescent optical luminosity, an aspect common to all disk instability models for these systems (Huang & Wheeler 1989; Mineshige & Wheeler 1989; Mineshige, Kim & Wheeler 1990).

One obvious possibility is that the blue optical flux observed in quiescence of A0620-00 is that of the hot spot generated by the transfer stream that is, to first order, constant during the whole outburst process. A0620-00, GS 2000+25, and Nova Muscae are strikingly similar objects in terms of their light curves. They also have similar orbital period and mass function, which suggests they have similar accretion disks. Eclipse mapping of GS 2000+25 in quiescence shows evidence for a hot spot which is much brighter than the disk itself (Casares, Charles & Marsh 1995). The bright spot in GS 2000+25 clearly implies that there is continuous mass transfer in quiescence, the major assumption of the disk instability model. The fact that the bright spot dominates the disk luminosity is consistent with the cold disk we predict in quiescence. The possibility that the hot spot contributed substantially to the quiescent optical emission of A0620-00 was discussed by McClintock *et al.* 1983). The optical/UV observations reported by McClintock, Horne, and Remillard (1995) show that the bolometric flux detected by HST is consistent with that expected from the transfer stream. They fit the continuum spectrum of the “disk” with a reddened 9000 K black body and for a distance of 1 kpc and derive an emitting area of $1.2 \times 10^{20} \text{ cm}^2$, 80 times smaller than the disk. The implied bolometric luminosity of this emission, assuming an optically thick sphere with this area and effective temperature, is $4.6 \times 10^{31} \text{ erg s}^{-1}$. The rate of release of potential energy by the transfer stream striking the outer edge of the disk at radius R_d is given approximately by $1.3 \times 10^{30} \dot{M}_{15}/R_{d,11} \text{ erg s}^{-1}$ where M is the mass of the compact object in solar masses, \dot{M}_{15} is the secondary transfer rate in 10^{15} g s^{-1} and $R_{d,11}$ is the outer disk radius

in units of 10^{11} cm. Clearly, for $\dot{M}_{15} \sim 30$, a plausible case could be made that all the optical luminosity arises in a hot spot and not in the disk proper. It is not clear whether ascribing all the optical luminosity to the hot spot is consistent with the lack of observed orbital modulation (McClintock, Horne & Remillard 1995).

There is still the question of the quiescent X-ray emission from A0620-00 which can be matched by the advection solutions with appropriate choices of parameters, but not with the present disk instability models. The advection solutions require some means of severely depleting the surface density of the inner portions of the disk as the disk approaches quiescence. It is difficult to see how such a solution matches physically in terms of the surface density and angular momentum with the outer thin quiescent disk. Perspective on this problem can be gained by considering some time scales inherent in the advection solution. The high temperature, low efficiency advection solutions require a very low density and hence a low mass in the advection region. The published solutions assume an *ad hoc* supply of mass from the Keplerian disk to the advection region in order to maintain this steady-state condition (Narayan, McClintock and Yi 1996; Lasota, Narayan, and Yi 1996). The disk instability models, on the other hand, give a much lower mass flow rate in quiescence. It is thus of interest to inquire how long the advective solution would survive if the mass flow were cut off. Using the expression for the density distribution given in Narayan, McClintock, and Yi and the parameters for their fit to A0620-00 ($\alpha = 0.1$, $M = 4.4M_{\odot}$, $\dot{M}_{15} = 0.4$), the mass is $1.9 \times 10^2 R_2^{3/2}$ g. For the derived mass flow rate in the advective region, the time to consume the advective region in the absence of mass input is $M/\dot{M} = 14 \text{ s } R_{a,9}^{3/2}$, where $R_{a,9}$ is the boundary between the advective region and Keplerian disk in units of 10^9 cm. Clearly, the advection region is very fragile and must be constantly supplied at the high mass flow rates required by the low radiative efficiency in order to be sustained. This is not a trivial requirement.

The high mass flow rate necessary to maintain the advective region, $\dot{M}_{15} = 0.4$, does not arise naturally in the quiescent disk instability models. It must, rather, be supplied from the matter in the Keplerian disk by some sort of ill-understood ablation process. One can at least ask what the implications are of supplying mass at this rate. To determine this, we fit an approximate power law to the quiescent disk structure of the models of Kim *et al.* (1996a,b), recognizing that this will be different for different viscosity prescriptions. For the quiescent mass distribution corresponding to Figure 5, we find

$$\frac{dm}{dr} = \frac{1}{v_a} \frac{dm}{dt} \sim 10^{13} r_{10}^{1.4} \text{ g}, \quad (5)$$

where $v_a = dR_a/dt$ is the speed with which the boundary of the advection region advances into the Keplerian disk and dm/dt is the rate of ablation necessary to feed the advection region. This implies a characteristic time scale to consume the disk of

$$\tau = \frac{R_a}{v_a} = 2.5 \times 10^8 R_{a,10}^{2.4} \text{ s}, \quad (6)$$

where $R_{a,10}$ is the outer boundary of the advection region in units of 10^{10} cm. The advection solution of Narayan, McClintock & Yi (1996) that reproduces the ROSAT X-ray observations cannot remain with an outer boundary of order 10^9 cm for times comparable to the recurrence time. If such an advection region is fed by ablation from the Keplerian disk 20 years after the outburst, the boundary must be in excess of 10^{10} cm. This seems to be a rather extreme criterion. An alternative is that the quiescent X-rays do not arise in the inner disk at all. The observed flux is low and it is possible that it arises in flare activity on the companion.

Clearly more work is needed to understand the state of the disk in both quiescence

and outburst. The black hole X-ray transients are excellent laboratories for these studies and the disk instability models give a framework in which to pose relevant questions.

8. The Hard Power Law, Radio Outbursts, and Positrons

The hard power law component that is frequently observed in black hole X-ray transients is very similar to that observed in AGN as discussed in these proceedings by Svensson. Since at some level we know more about the transient systems – the definite existence of accretion disks, orbital parameters and, in the best cases, masses of the components – we may, with some hubris, expect that these transient systems may help us to understand the hard radiation mechanisms of AGN, rather than the other way around.

It is commonly assumed that the power law component represents a Comptonized thermal spectrum arising in a hot plasma that is itself part of a coronal structure that is in hydrostatic equilibrium. Such a simple model for the emission can fit some objects at some epochs, but that does not make it unique or correct. Such models ignore the obvious evidence for non-thermal particles and magnetic fields implied by the common radio outbursts that are frequently associated with the X-ray bursts (Han and Hjellming 1992). The recent super-luminal sources are only the most extreme example. It is most likely that the non-thermal particles and magnetic fields arise in the disk and hence must be incorporated into models of the hard power-law emission. Kusunose has shown that thermal models are not unique. Non thermal models can produce power law emission that has a constant slope independent of luminosity, as observed (Kusunose & Mineshige 1995). In addition, there is ample evidence for outflow at least at some epochs and so there is reason to question the assumption of hydrostatic equilibrium for the plasma.

The soft X-ray component that probably arises in the accretion disk peaked more slowly than the hard power law flux in Nova Muscae. This may mean that the inner disk was incomplete in quiescence or the early phase of the outburst. The radius of the geometrically thin, optically thick disk may have shrunk in response to increased mass flow attendant with the disk instability in the outer disk, thus giving rise to the delayed rise of the soft flux. It may be that in systems like V 404 Cyg and GRO J0422+32, the inner disk never properly forms to give soft X-rays, for reasons that are not currently understood.

The first flare of the hard flux in systems like Nova Muscae may be better associated, not with a static, thermal plasma, but with a non-thermal, magnetic, pair-rich outflow (Moscoso & Wheeler 1994). This phase shows QPO's, correlated radio synchrotron bursts, and at least in Nova Muscae, the line feature that is plausibly associated with annihilation. If this is the annihilation line, then it is much too narrow to represent annihilation in the region where positrons are created and hence implies flow of some kind from the location of the creation of the positrons to the locale of their annihilation.

The “second maximum,” as defined here is primarily characterized by a hard power law spectrum and the virtual absence of a soft X-ray component from the inner disk. This feature may arise in a structure that more closely resembles a quasi-static corona of the sort frequently modeled in the literature (Liang 1990). The fact that the disk component of the soft X-ray flux declines as this late hard component comes up strongly suggests that the corona is displacing the geometrically thin disk. With a larger effective inner radius, the disk simply becomes too cool to emit soft X-rays.

There is some speculation that the “second maximum” may be related to an advection solution, but the problems associated with the time scales and the feeding of such a region by the outer thin disk outlined in the previous section may again apply. There is also some question of whether this feature could be related to a tidal instability that is

triggered when the disk radius grows beyond the 3 to 1 resonance due to the onset of the disk instability. The long time delay, 200 days, might be accounted for by the slow linear growth time of the instability (Ichikawa, Mineshige, & Kato 1994). It is not clear that this picture can naturally account for the X-ray spectral characteristics of the “second maximum.”

To better understand the possible origin of the power law in dynamical environments and the nature of the “annihilation feature” in Nova Muscae, Moscoso, Kusunose, and Wheeler are constructing a model to explore the source of the outflow in the primary outburst. This model consists of an inner hot, pair-rich corona represented by a single zone. Above this corona, photon annihilation will generate electron/positron pairs and associated annihilation. The parallel component of the average momentum of the photons that produce pairs is assumed to represent the bulk outflow momentum of pairs. The remaining momentum is randomized to provide the thermal component of the pair energy. Account will be taken of both the isotropic and anisotropic Comptonization. This simple model will give an estimate of the typical flow time scales, speeds, and the optical depth so that annihilation line profiles can be estimated.

9. Evolution

Many fascinating questions arise with respect to the evolution of these black hole transients. These involve the large mass ratios, the suggestion that the black holes may be rather moderate in mass, and the significance of lithium in some of them.

With typical primary masses of $5M_{\odot}$ and secondary masses of $0.5M_{\odot}$, the mass ratio of these systems, ~ 10 , is very large. Most massive binaries are thought to have mass ratios closer to unity, but there are clearly strong selection effects that bias observations away from such large ratios. Nevertheless if this is merely an accident of birth, it seems odd that it is the future black hole systems that favor small mass companions.

It is not clear how much the secondary may have altered during the evolution of the system (De Kool, van den Heuvel & Plyser 1987). Many of the secondaries seem to be at least slightly evolved, the secondary in V404 Cyg definitely so (Casares, Charles & Naylor 1992). The atmospheres, where they can be observed in quiescence, are, with some small exceptions, characteristic of main sequence stars, so they can not be highly evolved. They may have lost mass not only to Roche lobe overflow, but also to the process of being blasted by X-ray radiation at recurrent intervals since the black hole formed (Mineshige, Kim & Wheeler 1990). The small orbital periods that characterize these systems, suggest that they have been subject to common envelope evolution and ejection, but the low mass companions have little leverage on the envelope of the black hole progenitor and it is not clear how such systems could escape core coalescence. There is some speculation that the secondary was not primordial, but formed out of the envelope of the massive star by some adjunct process to creating the black hole (Podsiadlowski 1996).

There is increasing evidence that there are upper limits as well as lower limits to the masses of the black holes in these systems (see, eg, Chen, Shrader & Livio (1996) for a compilation). The upper mass limits are interestingly low, perhaps systematically substantially less than $10M_{\odot}$ in many cases. Rather tight limits have been derived for Nova Oph 1977 ($4.9 \pm 1.3M_{\odot}$; Remillard *et al.* 1996), GS 2000+25 ($5.9 - 7.5 M_{\odot}$; Filippenko, Matheson and Barth 1995), GRO J0422+32 (3.57 ± 0.34 ; Filippenko, Matheson, and Ho 1995), and Nova Sco ($4.0 - 5.2 M_{\odot}$; Bailyn *et al.* 1995). Nova Muscae has been estimated to be in the range $4 - 8 M_{\odot}$ (Chen *et al.* 1996). If a temporary eclipse by the disk was seen by Haswell *et al.* (1993) an upper limit of $5 M_{\odot}$ can be assigned to A0620-00. V

404 Cyg is the sole current exception with a mass that might plausibly be as large as $12 M_{\odot}$ (Shahbaz *et al.* 1994; but see Sanwal *et al.* 1996 for an upper limit).

The possible clustering of masses around $5 M_{\odot}$ would be entirely consistent with the notion that the decline rate is a measure of the mass of the compact object (divided by α_0 ; §5). In this interpretation, the commonly observed decline rate with an e-fold time of about 30 days would signify a common mass. An important caveat to this conclusion is the evidence that some neutron star systems also display a decline rate of nearly 30 days (Chen *et al.* 1996).

These masses suggest that the black holes did not simply form by the collapse of a massive star. Clearly the collapse of an entire massive star would give far larger masses. A more reasonable possibility is that the collapse only involved the core of the star, the envelope having been ejected in a wind or common envelope process. As a rule of thumb, the core of a massive star is about 1/3 the original main sequence mass. Since moderately massive stars are commonly presumed to give rise to supernovae and neutron stars, the progenitors of black holes might be expected to have main sequence masses in excess of $30 M_{\odot}$ (Shields and Wheeler 1973). This would make a core mass in excess of $10 M_{\odot}$, still too massive to account for the low estimates given above. There may be a need for some other evolutionary process.

One possibility is that the object that is now a black hole began its compact life as a neutron star. If there was a stage of rapid mass transfer, then the neutron star might have been swamped so that an envelope formed around it. The resulting object with a neutron star in the center and a quasi-static envelope supported by energy from the gravitational energy or nuclear burning of accreted matter is known as a Thorne-Żytkow Object (Thorne and Żytkow 1977). In such a case the neutron star might continue to accrete until it surpassed the stable mass limit and then collapse to form a black hole and consume the remainder of the envelope. The mass of the resulting black hole would be the sum of the neutron star plus the envelope and could be rather modest. This scenario would demand that the secondary lose substantial mass. The secondary would have to be evolved, as seems to be frequently the case, although it could retain a thin H blanket. This possibility would have to be reconciled with the atmospheric observations. Forming a Thorne-Żytkow Object rather than burying both stars in a common envelope would also presumably require special conditions. The possibility that the original star is consumed, but the current secondary spun off to coalesce anew is a complication that might be worth considering.

One interesting connection of Thorne-Żytkow Objects with the current population of black holes is lithium. The two black hole candidates that have sufficiently bright quiescent luminosity to be examined, V 404 Cyg (Martin *et al.* 1992) and AO620-00 (Marsh *et al.* 1994), have both revealed excess of lithium in the atmospheres of the companions. This observation cannot be a unique signature of black holes systems because lithium has also been detected in the neutron star system Cen X-4 (Martin *et al.* 1994), but it is nevertheless intriguing. No such lithium enrichment has been observed in nova-like systems containing white dwarfs (Martin *et al.* 1995).

The lithium is short-lived in convective stellar atmospheres, so the strong presumption is that it must be freshly created in these systems, not primordial. The most likely origin is by spallation in the atmosphere of the secondary by fast particles accelerated by processes near the black hole (or neutron star). Another possibility is that the lithium is created in the disk, where spallation is, if anything, more likely, but then the problem exists of preserving and transporting the lithium to the secondary star where it is observed. Yet another possibility, more remote, but perhaps not impossible, is that the lithium is associated with a Thorne-Żytkow Object precursor phase. Under some circumstances,

the deep convective burning in a Thorne-Żytkow Object can produce lithium (Cannon 1993; Biehle 1994; Podsiadlowski, Cannon, & Rees 1995). It is not clear that the modest mass Thorne-Żytkow Objects that would be the precursors of the modest mass black holes would have this property (this is perhaps more likely with the large mass black hole of V 404 Cyg), nor how the lithium could be transferred to and preserved in the atmosphere of the secondary.

The observation of the lithium excess also couples to one more conundrum in the black hole systems. The putative annihilation line in Nova Muscae and the corresponding broad feature that has appeared in 1E1740.7 (the “Einstein Source”) are, within the errors, centered at about 480 Kev, not 511 Kev. This has been interpreted as requiring that the annihilation occur sufficiently deeply in a gravity well that the shift can be attributed to a gravitational redshift (Chen, Livio & Gehrels 1993; Moscoso & Wheeler 1994). As it happens, one of the principle γ -ray de-excitation lines of lithium formed in spallation is at 483 Kev. This coincidence has given rise to considerable speculation that the “annihilation feature” is actually de-excitation of the newly forming lithium observed in the companion (Martin *et al.* 1992, 1994; Martin, Spruit, and van Paradijs 1994). Although there are some numerical coincidences, no quantitative model of spallation of the lithium has been provided to account for the observations. One counter argument is that there should be other associated spallation γ -rays that are not observed and a counter-counter argument is that there may be some hint, in Nova Muscae, that the 480 Kev feature has a double peak. It will take much better signal to noise to resolve that issue. The 480 Kev feature in Nova Muscae was accompanied by another, weaker line at 175 Kev which can be kinematically accounted for by a blue-shifted back scattering of the annihilation line (Hua and Lingenfelter 1993). It is not clear that a lithium model can account for this “back-scatter” feature. Other objections to the lithium interpretation are that the 480 Kev feature, while too narrow to arise in the region where positrons are created, has a finite width in both Nova Muscae and the 1E source. This means that the feature is unlikely to arise in the atmosphere of the secondary even though that is where the optical line of lithium is seen. The accretion disk is a more likely locale to produce such broad de-excitation lines by thermal or Doppler broadening. One might then have the inverse problem of the annihilation line interpretation, because if the line is from lithium, then it can suffer very little or no gravitational redshift. Clearly the interpretation of this feature as either lithium or positronium requires more careful quantitative analysis. Yet another possibility is that circumstances contrive to give the “line” as a result of continuum scattering in an appropriately beamed flow (Skibo, Dermer & Ramaty 1994).

10. Conclusions

The basic picture in which a companion star feeds mass at nearly a constant rate into an accretion disk that is susceptible to an ionization limit-cycle instability is still the most plausible explanation for the black hole X-ray transients. The characteristic light curve with a fast rise and exponential decline is consistent (even demands) that the instability begins in the outer portion, logarithmically, of the disk. In such a case, the optical emission should rise before any hard emission. This is difficult to check with current search techniques, but something like an all sky optical monitor could provide critical constraints on this important qualitative prediction.

As the heating wave propagates inward and leads to a dramatic increase in the flow rate in the inner disk, one might expect outflows to be generated. These outflows could then, in turn, be related to the ubiquitous radio bursts including, in the most extreme

cases, the superluminal sources, and the occasional observation of annihilation lines. If the outflow region interdicts the inner portion of the accretion disk so that the optically thick, geometrically thin disk can not, at first, extend down to the last stable circular orbit, then the disk may be too cool to emit X-rays. This may be why the hard flux arises earlier than the soft flux in Nova Muscae despite the prediction that the instability should begin in the outer disk.

In this picture, the hard power law flux associated with the onset of primary outburst in the fast-rise, exponential decline systems, should be associated with an outflow, probably pair rich and magnetic, not in a quasi-static corona, nor even in a quasi-radial advective region. An important task is to develop physical models that can help to discriminate these various possibilities. This is the stage at which systems like Nova Muscae display the strongest QPO's and hence one is invited to examine models for QPO's that do not directly involve only the disk or a radial inflow, but a dynamic outflow.

After a period of order a few days after the rise of the hard flux, the disk may settle into a quasi-steady declining state where it can emit copious soft X-rays and the hard power law source, perhaps in the outflow, declines rather more sharply. The exponential decline of the soft X-rays is a critical constraint on the physical nature of the disk. It is completely consistent with the predictions of the disk instability model, demands that a cooling wave be propagating in the disk during the decline, and is consistent only with a tightly-constrained prescription of the disk viscosity. There is only one self-consistent model for disk viscosity in the literature that fulfils these constraints, that based on a magnetic dynamo driven by internal waves.

The common "reflare" phenomenon during the exponential decline may be related to the self-irradiation of the disk. The fact that it occurs in Nova Muscae as the hard component reaches a minimum may be a clue that requires pursuing. It is not at all clear that this feature is related to a modulation of the mass transfer from the companion.

The common "second maximum" is dominated by a hard power law source in Nova Muscae rather than the disk thermal radiation, and presumably also in other similar systems. This phase tends not to be accompanied by QPO's. The power law source in this phase may arise in a quasi-static corona of a more traditional sort that can arise as mass flow rates decline. Although the spectral index is similar, this phase may thus involve a very different physical environment than the first epoch of hard power law emission that is dominated by outflow. The formation of this coronal region in the inner disk may again interdict the inner optically thick disk so that the emission of soft X-rays is inhibited. This could account for the precipitous decline in the disk component of the soft X-rays in Nova Muscae as the hard power law source grows to dominate the "second maximum." The "corona" associated with the "second maximum" may be related to an advective flow, but the current advective models have been fit to the much later, currently observed quiescent phase of AO620-00 and it is not clear that they can naturally account for the transient behavior of the "second maximum." At any phase there are some difficult questions to be addressed as to how the relatively high mass flow rates of the advective solutions can be stably fed by the naturally low mass flow rates in the quiescent Keplerian disk.

The black hole X-ray transients provide a continuing source of stimulating physics problems worthy of Igor Novikov. Their time-dependence and multi-component spectra, while a complication, may yet yield the sort of direct irrefutable evidence that we are dealing with black holes that is one of the holy grails of modern astrophysics. As a practical matter, this would allow us to search for and identify black holes of stellar mass in a way that is not possible when one is restricted to argument by mass function that "it is too massive to be a neutron star." Finally, with the lessons learned in these

marvelous laboratories, we will be more strongly armed to attack the stubborn problem of the nature of QSO's and AGN's and their supermassive black holes.

I would like to thank all my colleagues who have taught me so much about black hole systems and accretion disks, especially John Cannizzo, Pranab Ghosh, Min Huang, Shin Mineshige, Soon-Wook Kim, Michael Moscoso, Greg Shields, Rob Robinson, Ethan Vishniac, and Masaaki Kusunose, with whom I have had the pleasure of working at Texas on these issues. This work has supported in part by NASA through grants NAGW-2975 and NAG5-3079.

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